Multi-channel and single-channel venous occlusion plethysmography for finger blood flow measurement

A.J.L. WELSH, M.J. GRIFFIN

Human Factors Research Unit, Institute of Sound and Vibration Research, University of Southampton, Highfield, Southampton SO17 1BJ, England

Abstract

Using venous occlusion plethysmography, three experiments have been conducted to investigate factors affecting the measurement of finger blood flow in a group of 12 male subjects. It was found that finger blood flow was similar when measured simultaneously on all five fingers of the hand and when measured on a single finger. Variations in the occlusion pressure (from 30 mmHg to 100 mmHg) influenced the rate of change in finger volume, but when extreme pressures were excluded the measurements appeared repeatable. The height of the hand relative to the heart affected the measured blood flow, but with little change between heart level and 250 mm above the heart.

1. Introduction

Vascular disorders caused by occupational exposures to hand-transmitted vibration are associated with a variety of symptoms and signs. The principal vascular disorder, vibration-induced white finger, is sometimes considered to be characterised by episodic complete closure of digital blood vessels during which there is no blood flow in the affected area.

The diagnosis of vibration-induced white finger requires the occurrence of attacks of well-demarcated finger blanching, with attacks normally commencing with blanching in the distal phalanges and possibly extending to other more proximal phalanges before receding to the distal phalanges and recovery. The symptoms and signs of vibration-induced white finger appear in situations in which there is reduced digital blood flow. Apart from exposure to vibration, attacks are mainly provoked by exposure to cold conditions, although cold will not always provoke an attack. Some of those with vibration-induced white finger report that their fingers often feel abnormally cold, even without a blanching attack. It seems that in some conditions there is an excessive reduction in blood flow resulting in finger blanching.

Current methods for diagnosing vibration-induced white finger include the measurement of finger systolic blood pressures and monitoring rewarming times following cold provocation. In such tests, blood flow is monitored indirectly, such as with measures of finger skin temperature. However, finger skin temperature is highly dependent on personal and environmental variables and is not a reliable indicator of digital blood flow. Although they tend to be correlated, the relationship between finger blood flow and finger temperature is complex and one measure cannot be inferred from the other.

Blood flow has been used as an indicator of acute local and central changes consequent upon exposure to various types of hand-transmitted vibration (e.g. [1, 2, 3]), but standardised methods of measuring blood flow for the diagnosis of vibration-induced white finger have not been established. There are various artefacts that might affect measurements and their interpretation and several independent variables that may influence measurements, for example the occlusion pressure, differences between fingers, number of occluded fingers and the location of the measured hand.

Greenfield *et al.* (1963) state that arterial inflow is unaffected over a wide range of sub-diastolic pressures and that that pressure in the distal arteries is unaffected when a cuff is inflated at any sub-diastolic pressure. One study has reported that the basal critical closing pressure for digital arteries in thermo-neutral conditions varies between subjects from about 10 to 60 mmHg [1]. It is not known whether the blood flow varies between fingers or whether the simultaneous measurement on more than one finger affects measurements when using venous occlusion plethysmography.

The location of the measurement site relative to the heart might affect the measured blood flow. Greenfield [4] measured blood flow in a large limb above heart level to encourage free venous drainage. Greenstein and Kester [5] measured blood flow above the level of the heart with the subject supine, whereas some others have measured blood flow with the subject in a seated position. Bovenzi and Griffin [1] measured blood flow at different hand heights above the heart with seated subjects in order to establish a pressure-flow relation in the fingers.

The purpose of this study was to investigate factors that may affect the measurement of finger blood flow (FBF) for diagnostic purposes. This included a comparison between two similar methods of measuring blood flow using venous occlusion plethysmography.

Three separate experiments were conducted to: (i) compare simultaneous measurements on five fingers with measurement on one finger alone, (ii) investigate the effect of different cuff inflation pressures on results, (iii) investigate the differences between digits, and (iv) investigate the effect of elevating the hand relative to the heart.

The hypotheses were:

(1) Simultaneous measurements on five fingers will not produce a different FBF from measurements on a single finger;

(2) There will be no difference in finger blood flow between the five fingers;

(3) Varying the cuff occlusion pressure will affect the reliability of FBF measurements;

(4) Varying the height of the hand relative to the heart will affect FBF measurements.

2. Method

2.1 Subjects

Subjects attended one session during which finger blood flow measurements were measured using both methods. Twelve healthy male subjects were selected from university staff and student populations. Subjects ranged in age from 20 to 45 years. Subjects were non-smokers, not taking any medication at the time of the experiment, had no prior occupational exposure to hand-transmitted vibration and had not consumed tea or coffee within an hour prior to testing.

2.2 Experimental Conditions

The experiment was conducted in a quiet room at 25°C (±2°C). Subjects, who were acclimatised for 10 minutes at room temperature before commencing the test, lay supine on a clinic bench with the left arm supported at heart level (except where specified). Watches and jewellery were removed to avoid restricting blood flow. Finger skin temperature was measured at the start of each part of the experiment.

2.3 Experimental design

2.3.1 Measurement of finger blood flow

Arterial blood flow to the fingers was measured by the venous occlusion strain gauge plethysmography technique, according to the method proposed by Greenfield [4]. Mercury-in-silastic strain gauges were placed around the distal phalanges, and cuffs were fixed around the proximal phalanges. The cuffs were connected to the pneumatic system of a plethysmograph. The plethysmograph also measured the resistance of the strain gauges, which increased as the finger circumference increased with increasing finger volume when there was a net inflow of blood into the finger during venous occlusion. The change in resistance (proportional to strain) was recorded as a percentage change from the baseline resistance measured during calibration.

In order to avoid artefacts during inflation, the cuffs were positioned on the proximal phalanges of the digits and the strain gauges were placed around the distal phalanges [4]. The strain gauge was always in slight extension but not so tight as to restrict blood flow. The method assumes that the digit is cylindrical and changes in volume in the transverse direction and not in the longitudinal direction.

The plethysmograph was calibrated by connecting two dummy electrical resistors: a resistance of 0.5 ohms in parallel with a 50 ohm resistor, and a resistor of 10 ohms in parallel with a 100 ohm resistor. The occlusion pressure was calibrated by measuring the pressure achieved at the cuff with a manometer in comparison with the pressure supplied by the plethysmograph.

Before each FBF measurement, the resistance of the strain gauge was measured before occlusion. Venous occlusion was then applied by instantly inflating the pneumatic cuffs to the required pressure (between 30 and 100 mmHg, depending on the part of the experiment). The subsequent rise in volume of the fingertip was monitored from the changing resistance of the strain gauge over a period of a few seconds. The finger blood flow was calculated from graphical records of the changing resistance of the strain gauge using the method suggested by Greenfield *et al*. [4].

In rapid succession, five good traces of arterial inflow were obtained from each subject for each measurement condition and the mean value calculated. The finger blood flow measurements were expressed as ml/100 ml/min.

2.3.2 Equipment

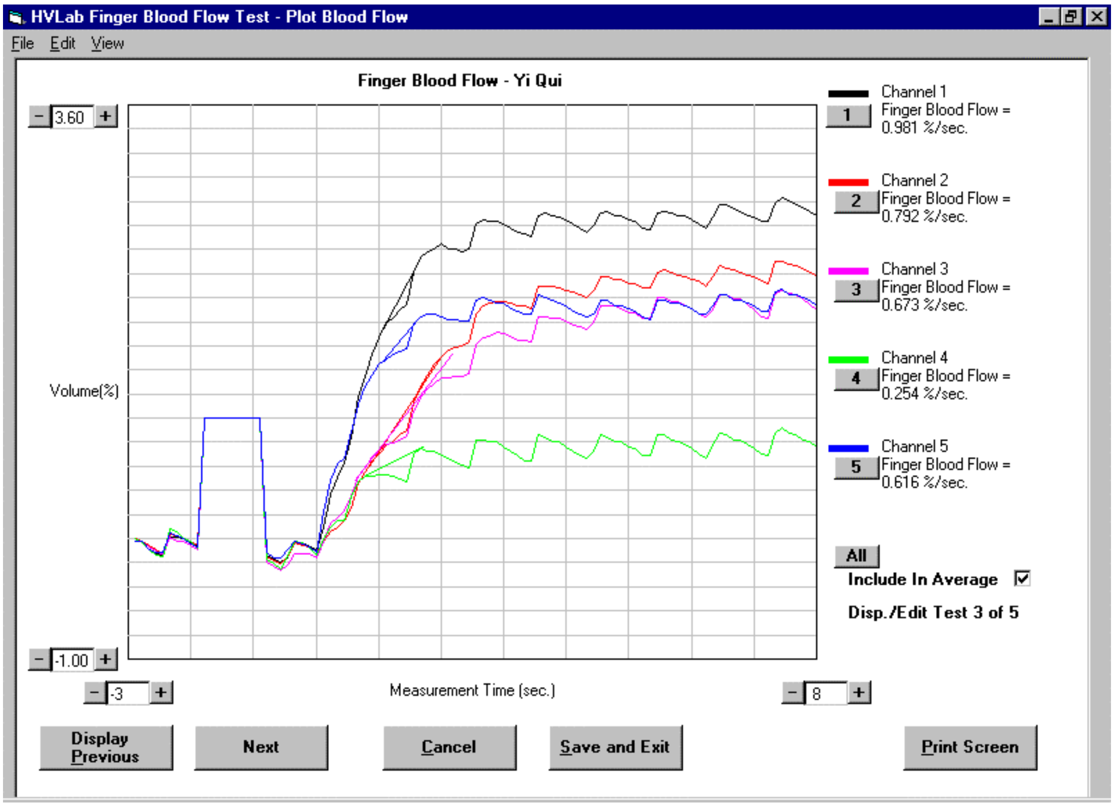
The *HVLab* (ISVR, University of Southampton) plethysmograph was employed. Throughout the experiment, the pneumatic occlusion pressure was achieved using the same cuffs and the same plastic tubes, and the lengths of tubing between machine and hand (83 cm) were kept constant.

2.3.3 Interpretation of finger blood flow

The *HVLab* plethysmograph is computer controlled. The plethysmograph provided a chart that indicates the increase in finger volume (which is assumed to be proportional to the increase in strain gauge resistance) over time. The gradient of the trace after venous occlusion is assumed to indicate the rate at which blood enters the finger. The blood inflow, A_{in}, was measured in ml of blood per 100ml tissue per second (which is equivalent to the percentage increase in finger volume per second), calculated by the computer from the graphs using:

$$A_{in} = \frac{C}{A.E}$$

where A (mm) is the height of a calibration pulse corresponding to a 1% increase in finger volume, and C (mm) is the increase in height of the blood flow curve over period E (s). See example blood flow curve in Figure 1.



Channel 1
Finger Blood Flow = 0.981 %/sec.

Channel 2
Finger Blood Flow = 0.792 %/sec.

Channel 3
Finger Blood Flow = 0.673 %/sec.

Channel 4
Finger Blood Flow = 0.254 %/sec.

Channel 5
Finger Blood Flow = 0.616 %/sec.

Include In Average ☑

Disp./Edit Test 3 of 5

Figure 1: Finger blood flow trace (60mmHg occlusion pressure, 8 second occlusion duration)

Changes in finger volume were determined by fitting a tangent to the blood flow curves following venous occlusion. Standardised positioning of the slope was needed to maintain consistency across measurements. The first 1-second of the blood flow curve after venous occlusion was ignored as this sometimes contains artefacts caused by the pressurisation of the cuff. The tangent was formed from a line joining either the systolic peaks or the diastolic troughs of the blood flow curve over the steepest period between 1 second and 2 seconds after the application of the occlusion pressure.

The slope of the blood flow curve was estimated automatically from the increase in strain, but the experimenter can review and adjust the slope if necessary. The computer records the blood flow corresponding to the slope.

The plethysmograph estimates strain gauge resistance by measuring the voltage across the terminals with constant current excitation. The *HVLab* plethysmograph used a four-terminal arrangement making it possible to directly measure the resistance across the strain gauge, eliminating error due to cable resistance. The system allowed simultaneous measurements of blood flow at five locations; and stored individual blood flow curves as well as individual and mean slopes within the computer.

2.3.4 Design and Procedure

The experiment was divided into three parts.

Part One: Comparison of simultaneous measurements on five fingers with measurement on one finger

Finger blood flow was measured with the *HVLab* plethysmograph on the middle left finger in two conditions: (i) when all five fingers on the left hand were occluded, and (ii) when only the middle left finger was occluded. The order of testing was balanced such that six subjects were tested first with five fingers occluded and six subjects commenced with one finger occluded.

When measuring on a single finger, a single cuff and a single strain gauge were used on the left hand and the other four cuffs were placed on the right hand. Five consecutive finger blood flow measurements were obtained, with a pressure of 60 mmHg applied for 8 seconds.

Part Two: Cuff inflation pressure

Using the *HVLab* plethysmograph, finger blood flow was measured simultaneously on all fingers of the left hand with nine cuff occlusion pressures. The order of presenting the occlusion pressures was randomised. Five consecutive finger blood flow measurements were obtained, with a pressure applied for 8 seconds at: 30 mmHg, 40 mmHg, 50 mmHg, 60 mmHg, 70 mmHg, 80 mmHg, 90 mmHg, or 100 mmHg.

Part Three: Elevating the hand relative to the heart

Using the *HVLab* plethysmograph, the finger blood flow was measured simultaneously on all fingers of the left hand with the hand level with the heart, 250 mm below the heart and 250 mm above the heart. Five consecutive finger blood flow measurements were obtained, with a pressure of 60 mmHg applied for 8 seconds.

2.5 Statistical Methods

Data analysis was performed with the software package SPSS (version 10.0). The data were summarised with the median as a measure of central tendency and the inter-quartile range as a measure of dispersion. Non-parametric tests (Friedman test for *k*-related samples and the Wilcoxon matched-pairs signed ranks test for two-related samples) were employed in the statistical analysis.

3. Results

Part One: Comparison of simultaneous measurements on five fingers with measurement on one finger

There was no significant difference between finger blood flow measurements on the middle finger when measured alone or when measured at the same time as the other four fingers on the same hand ($p = 0.937$). The median (IQR) measures of finger blood flow were 0.589 ml/100ml/sec (0.462) when measuring on only one finger and 0.503ml/100ml/sec (0.404) when measuring on all five fingers.

Part Two: Cuff inflation pressure

In all five fingers, changes in occlusion pressure resulted in a significant variation in the indicated finger blood flow (Friedman, $p < 0.001$; see Table 1).

On each finger, the statistical significance of the differences between measures for all pairs of occlusion pressures were determined (Table 2; Wilcoxon $p < 0.05$).

Table 1 Median (inter-quartile range) of finger blood flow (ml/100ml/sec) indicated for each finger at each occlusion pressure. Pressures below about 60 mmHg probably resulted in some erroneous indications of finger blood flow.

Occlusion Pressure (mmHg)	Finger1	Finger 2	Finger 3	Finger 4	Finger 5
30	0.152 (0.087)	0.074 (0.056)	0.134 (0.085)	0.106 (0.157)	0.050 (0.083)
40	0.245 (0.250)	0.150 (0.136)	0.245 (0.280)	0.163 (0.112)	0.136 (0.161)
50	0.412 (0.325)	0.364 (0.238)	0.554 (0.234)	0.386 (0.287)	0.351 (0.183)
60	0.499 (0.303)	0.413 (0.314)	0.609 (0.502)	0.370 (0.287)	0.303 (0.330)
70	0.662 (0.496)	0.671 (0.627)	0.961 (0.526)	0.665 (0.437)	0.693 (0.394)
80	0.646 (0.312)	0.696 (0.400)	0.893 (0.532)	0.800 (0.408)	0.654 (0.343)
90	0.765 (0.333)	0.764 (0.404)	0.823 (0.636)	0.700 (0.572)	0.561 (0.319)
100	0.787 (0.570)	0.926 (0.548)	0.864 (0.401)	0.815 (0.522)	0.670 (0.490)

Table 2 shows that there were no significant differences between blood flow measured with 70, 80, 90 and 100 mmHg occlusion pressures. In most fingers there was a significant difference between indicated blood flow measured at 30 and 40 mmHg and that indicated when using higher occlusion pressures. This is because some of the lower pressures were insufficient to produce venous occlusion: the indicated blood flow measured on some subjects with low pressures was not indicative of true blood flow. Of the traces obtained with 30 mmHg occlusion pressure, 58% showed a pulse that overpowered the inflow trace or an artefact following application of the pressure that was large relative to any inflow. It appeared that 33% of measurements at these pressures were of a typical shape while 8% showed no inflow or clear pulse or were erratic. At 40 mmHg, traces were of a typical shape, showing a smooth arterial inflow followed by a levelling and the appearance of a pulse**.** At 70 to 100 mmHg the traces also show a smooth arterial flow, with no jump.

There were no significant differences between blood flows (in ml of blood per 100ml tissue per second) measured on different fingers (see Table 1) (except at 50 mmHg; Friedman, $p = 0.019$) where finger 3 gave a higher blood flow than finger 2 ($p = 0.004$) and finger 5 gave a lower blood flow than finger 3 ($p = 0.023$).

Table 2 Sum of significant differences between occlusion pressures (mmHg) over the five fingers (x = statistically significant difference between finger blood flows at the two occlusion pressures, one cross per finger, $p < 0.05$, Wilcoxon)

Occlusion Pressure (mmHg)	30	40	50	60	70	80	90	100
100	xxxx	xxxxx	xxxx	xx				
90	xxxx	xxxxx	xxxx	xx				
80	xxxx	xxxxx	xxxx	xxx				
70	xxxx	xxxxx	xx	xxxx				
60	xxxx	xxxxx			xxxx	xxx	xx	xx
50	xxxx	xxxxx			xx	xxxx	xxxx	xxxx
40	xxx		xxxxx	xxxxx	xxxxx	xxxxx	xxxxx	xxxxx
30		xxx	xxxx	xxxxx	xxxx	xxxx	xxxx	xxxx

The inter-quartile range in indicated blood flow at 50 mmHg shows less variance, and therefore a stronger measure of central tendency in fingers 2, 3 and 5 than in fingers 1 and 4 (Table 1).

The inter-quartile range in the indicated finger blood flow for each finger at 30 mmHg and 40 mmHg showed less variance in scores than at 60 mmHg (Table 1). The variance then increased as pressure increased.

Part Three: Elevating the hand relative to the heart
All five fingers showed significant changes in blood flow with change in elevation relative to the heart (Friedman, $p < 0.001$; Table 3).

There were no significant differences between measures of finger blood flow within any finger at heart level and 250 mm above the heart (Wilcoxon, $p > 0.05$), but there were significant reductions in blood flow in each finger when the hand was lowered to 250 mm below heart level ($p < 0.02$).

4. Discussion

There were no significant differences between five successive measures with the plethysmograph. This suggests that there is no learning, habituation

Table 3 Median (inter-quartile range) of finger blood flow (ml/100ml/sec) for each finger at three elevations of the hand.

	250 mm above heart	Level with heart	250 mm below heart
Finger 1	0.759 (0.516)	0.558 (0.339)	0.137 (0.091)
Finger 2	0.444 (0.539)	0.477 (0.268)	0.137 (0.144)
Finger 3	0.480 (0.286)	0.582 (0.684)	0.151 (0.070)
Finger 4	0.444 (0.365)	0.532 (0.391)	0.144 (0.087)
Finger 5	0.525 (0.393)	0.537 (0.463)	0.119 (0.116)

or adaptation during a set of rapidly repeated measurements of blood flow.

The absence of an affect of occluding blood flow in other fingers on the finger blood flow in the middle finger indicates that it is possible to use the multi-channel plethysmograph to simultaneously measure the blood flow of all five fingers of the same hand.

Changing the occlusion pressure produced a significant difference in the indicated finger blood flow within each finger. In order of sensitivity to occlusion pressures, the most sensitive digit was the ring finger, followed by the little finger and the index finger; with the thumb and middle finger least sensitive (Table 1). This seems reasonable considering the inherent physiological differences in blood flow between fingers.

The occlusion pressure normally used for measuring blood flow is a sub-diastolic pressure of 60 mmHg for all fingers. This pressure gave significantly different FBF measurements from those at 50 mmHg in all fingers and from those at 70 mmHg in the thumb, index and middle fingers. This is not consistent with the suggestion from Greenfield *et al.* [4] that occlusion pressure is not critical, provided it is a sub-diastolic pressure. When comparing the blood flow in each finger at each pressure, the only significant difference between fingers was found at 50 mmHg. It seems possible that the most sensitive range for occlusion was within the 50 to 70 mmHg range.

Although significant differences were found between 30 mmHg and all other occlusion pressures, this could be due to unreliable traces. If it is assumed that subject finger blood flow did not change with the different pressures, it was the ability to measure the blood flow that altered. With the occlusion pressures at about 80mmHg (and above) the pressure may not be sub-systolic in some subjects; the increased range in median blood flow was indicative of increased individual differences.

Hand elevation affected finger blood flow in a consistent manner across all fingers: blood flow was lower with the hand below heart level, consistent with the recommendations of Greenfield *et al.* [4] that sensitivity of readings is dependent on adequate venous drainage. The findings suggest that the hand should be at or above heart level. Further research should investigate whether it is necessary for a subject to be supine during the measurement of finger blood flow.

Although venous occlusion plethysmography may provide useful indications of changes in finger blood flow, it is not clear how accurately the indicated measures of blood flow reflect absolute measures that may be indicated by other methods. It may even be expected that there could be appreciable differences between absolute measures of blood flow indicated by different venous occlusion plethysmographs.

5. Conclusions

There was no significant difference in finger blood flow on the middle finger when occluded singly or occluded with the other four digits of the same hand. Multi-channel venous occlusion seems to be as reliable and as sensitive as single-channel venous occlusion.

Varying the occlusion pressure gave rise to significant changes in the indicated blood flow of each finger. The methods allow the apparent measurement of finger blood flow when the pressure is too low to cause venous occlusion and too high to allow full arterial inflow. The traces provided in these conditions might be mistaken for typical responses and used to calculate a blood flow. Pressures in the range 50 to 70 mmHg seem to result in measurements that may be reliably interpreted as indicative of finger blood flow.

It is necessary to maintain the occluded hand at, or above, heart level; however, small variations in hand elevation above heart level did not affect the indicated blood flow.

6. References

[1] BOVENZI M, GRIFFIN MJ. Haemodynamic changes in ipsilateral and contralateral fingers caused by acute exposures to hand transmitted vibration. Occupational and Environmental Medicine, 1997: 54, (8) 566-576.

[2] BOVENZI M, GRIFFIN MJ, RUFFELL CM. Acute effects of vibration on digital circulatory function in healthy men. Occupational and Environmental Medicine, 1995: 52:834-41.

[3] BOVENZI M, LINDSELL CJ, GRIFFIN MJ. Acute vascular responses to the frequency of vibration transmitted to the hand. Occupational and Environmental Medicine, 2000: 57, (6), 422-430.

[4] GREENFIELD ADM, WHITNEY RJ, MOWBRAY JF. Methods for the investigation of peripheral blood flow. British Medical Bulletin 1963:19:101-9.

[5] GREENSTEIN D, KESTER RC. Acute vibration – its effect on digital blood flow by central and local mechanisms. Proceedings of the Institution of Mechanical Engineers, 1992:(H)206, (2), 105-108

[6] LEWIS CL. The development of a multi-channel Plethysmograph. Presented at the United Kingdom Informal Group Meeting on Human Response to Vibration held at MIRA on the 18th to 20th September 1996.